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Highlights of recent results from the CMS experiment at the Large Hadron Collider

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After the first three years of operation, the Large Hadron Collider delivered an impressive amount of proton-proton collision data. The CMS experiment recorded approximately 5 fb^{-1} at $\sqrt{s}$ =7 TeV and 20 fb^{-1} at $\sqrt{s}$ =8 TeV. A wealth of results have been obtained with those data. Some of the most recent results on top quark physics, searches for supersymmetry and for other new physics models are discussed. The most notable result is the observation of a new particle with a mass of 125 GeV, with characteristics similar to those of the Higgs boson.

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The CMS experiment at the Large Hadron Collider (LHC) at CERN has produced a wealth of results based on the first three years of data-taking, ranging from the "re-discovery" of the standard model (SM) to searches for new physics (NP) beyond the SM. Certainly, the most notable achievement is the discovery of a new boson at a mass of approximately 125 GeV. The first three years of operation have been remarkable, not only in terms of the scientific results obtained, but also on the quick "ramping up" of the understanding of the detector up to precise measurements. The excellent understanding of the detector, exceeding some of the most optimistic expectations, is largely based on the long and intense phase of detailed planning, construction, testing, and commissioning, and lasted approximately the 20 years that preceded the data-taking period.

The CMS detector is a fantastic tool of gigantic proportions. The CMS detector measures particles produced in high-energy proton-proton and heavy-ion collisions with high granularity and excellent energy and position resolution. The central feature of the detector is a superconducting solenoid 13 m long, with an internal diameter of 6 m. Within its volume it generates a uniform 3.8 T magnetic field along the axis of the LHC beams. Within the field volume are a silicon pixel and strip tracker, a lead tungstate (PbWO4) scintillating crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter. Muons are identified and measured in gas-ionization detectors embedded in the outer steel magnetic-flux-return yoke.

After the startup on September 10th 2008 and the subsequent September 19th incident which caused a large disappointment and a full additional year of delay in the schedule, the LHC went on to deliver proton-proton collisions in the fall of 2009. Since then, physicists working at the LHC experiments have analyzed data coming first from low-luminosity and low-energy collisions, and then gradually from higher energy and higher beam intensity runs. After the very early data-taking periods at $\sqrt{s}$ =900 GeV in 2009, the experiment collected 36 inverse picobarns in 2010 and 5 fb^{-1} in 2011 at $\sqrt{s}$ =7 TeV, and approximately 20 fb^{-1} in 2012 at $\sqrt{s}$ =8 TeV. The data collected in 2009 was mainly used for the early commissioning and calibration of the detector, the 2010 data for the rediscovery of the SM, and 2011 for the first precise measurements at the LHC. With the large dataset collected in 2012, the LHC experiments have made the first leap into the “discovery” phase. A new boson with similar characteristics to those of the Higgs has been found, and the predicted $B_s^0 \to \mu^+\mu^-$ rare decays are within reach. Furthermore, the large dataset collected in 2012 will serve as a benchmark for the searches for NP to be improved in the near future.

1. Top quark physics: a tool for discovery

Many years after its discovery, the top quark still plays a fundamental role in the program of particle physics. The study of its properties has been extensively carried out in high energy hadron collisions. However, a few important questions still remain unanswered. Why is it so heavy? Is its mass generated by the Higgs mechanism? What is the role of the top quark in the electroweak symmetry breaking (EWSB) mechanism? Does the top quark play a role in non-SM physics?

The LHC is a “top quark factory” which produced one million of top quark events per experiment in 2011 alone. At hadron colliders, top quarks are mostly produced in pairs through strong interactions, or individually (single-top production) via electroweak interactions. At the Tevatron top quark pairs are predominantly produced in quark-antiquark annihilation (90%), whereas at the LHC the top quark pair production mechanism is dominated by gluon fusion process ($\simeq$ 80% at

$\sqrt{s} = 7$ TeV). This is due to the large gluon density in the proton at small-x. Several properties of the top quark have been studied, and these include studies of the kinematical properties, measurement of the production cross section, reconstruction of $t\bar{t}$ pairs in the fully hadronic final states, study of τ leptons in top quark decays, and reconstruction of hadronic decays of the W boson from top decays. The production cross section has been measured in many different final states, and deviations from the predicted SM values may indicate NP processes.

In each top quark pair event, there are two W bosons and two bottom quarks. From the experimental point of view, top quark pair events are classified according to the decay mode of the two W bosons: the all-hadronic final state, in which both W bosons decay into quarks, the lepton+jet final state, in which one W decays leptonically and the other to quarks, and the dilepton final state, in which both W bosons decay leptonically. The word "lepton" here refers to electrons and muons, whereas τs are somehow classified differently, and they are generally treated separately. In the dilepton channel, the final state consists of two charged leptons, missing transverse energy, and at least two b jets. The branching ratio is small (5%) and the background (mostly Z+jets) is also small, which makes the dilepton the best final state to select a clean sample of top quark events. The all-hadronic final state has an experimental signature with at least 6 jets, of which two are from b quarks, with a large background, mostly from QCD multijet events. Due to the large background, the measurement of the cross section in this channel is rather difficult, despite the large branching fraction (44%). The lepton+jet final state offers a compromise with a reasonably large branching fraction (36%) and a moderate background, mostly from W+jet events. The signature consists of one charged lepton, missing transverse energy, and at least four jets (two of them b-jets).

Cross section measurements have been performed both at the Tevatron and at the LHC and the accuracy of the experimental results rivals that of theory expectations. At the Tevatron ($\sqrt{s} = 1.96$ TeV), the top quark pair production cross section is measured very precisely as $\sigma = 7.50 \pm 0.48(\mathrm{stat.} + \mathrm{syst.})$pb [1] (6% precision). The first top quark pair candidates at the LHC were already reported in the summer of 2010, after a few months of data-taking at $\sqrt{s} = 7$ TeV. After two years, thousands of top quark events have already been selected. Measurement of the inclusive top quark pair production cross section have been performed at the LHC in the dilepton and lepton+jet channels using electrons and muons and provide the most precise results [2]. Most of the cross section measurements are already limited by the systematic uncertainties. Measurement are also performed in the tau+lepton, tau+jets, and all-hadronic channels. The interest of determining the cross section in all channels is mainly to check the consistency of the measurements. For example, the measurement of the cross section in the tau+lepton (as well as the tau+jets) final state is important because a deviation of the measured cross section from the expected value may provide a hint for NP. The tau+lepton channel, i.e. $t\bar{t} \to (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ (with $\ell = e, \mu$) is of particular interest because the existence of a charged Higgs with a mass smaller than the top quark mass $m_{H^+} < m_t$ could give rise to anomalous tau lepton production directly observable in this decay channel, via $t \to H^+ b$. As in the other channels, the tau+lepton cross section results [3] are consistent with the cross sections measured in the other final states, and the measurement can be used to set stringent limits on charged Higgs production [4].

The large number of top quark events collected makes also possible the measurement of differential cross sections, $d\sigma/dX$, for the relevant variable X. For instance, variables of relevance may be related to the kinematics of the top or $t\bar{t}$ systems, such as p_T, $m_{t\bar{t}}$, $t\bar{t}$+N jets. These distributions may be used to validate given MC models as well as to check specific higher order QCD calculations. Deviations could signal contribution from NP. The electroweak couplings of the top quark can also be studied in the associated production to a gauge boson, such as $t\bar{t}\gamma$, $t\bar{t}$W, and $t\bar{t}$Z events. Results agree well with SM predictions [5].

The top quark mass m_t is a fundamental parameter of the SM, and it is linked to the W and Higgs boson masses. Through its measurement it is possible to constrain indirectly, together with the W mass, the Higgs boson mass value. It is measured precisely at the Tevatron with an accuracy of about 0.5%. The combined value from the CDF and D0 experiments yields $m_t = 173.2 \pm 0.9$ GeV [6]. Direct measurements of m_t are also performed at the LHC. Many techniques [7] have been used, and the most accurate single measurement at the LHC is performed with the "Ideogram" method, in which a constrained kinematic fit is performed for all jet-parton assignment combinations. In the lepton+jet channel, reduced uncertainty can be achieved with an in-situ calibration of the W mass from the untagged jets, using the $W \to qq'$ decays. An accuracy of 0.6% is reached, comparable to the one measured at the Tevatron.

Single top is produced through electroweak interactions in the s- and t-channels, and in association with a W boson (tW-channel). With a cross section which is a fraction of the top quark pair production, single top has a much larger relative background, and it is therefore more complicated to identify. Due to the relatively large background, it was first observed at the Tevatron only in 2009 with the help of multivariate analyses. The dominant production mode is through the t-channel both at the Tevatron and at the LHC; it has the cleanest signature with a light quark jet recoiling against the top quark. With a very small cross section (yet too small to be observed individually), the s-channel is rather interesting as it is sensitive to various NP processes. Among others, it is directly proportional to the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$ and it is sensitive to the presence of a W' boson or flavor changing neutral current (FCNC) processes.

Properties of the top quark are not only interesting to better characterize this fundamental particle, but could also give indication of NP. Measurement of the ratio of branching fractions $R = BR(t \to Wb)/BR(t \to Wq)$, top quark pair spin correlation, W polarization in top decays, asymmetry in $t\bar{t}$ events are some interesting properties. In the SM, the top quark is expected to decay as $t \to Wb$ with a branching fraction close to 100%, as top quark decays to a W boson and a quark in a different isospin doublet are strongly suppressed. The magnitude of the CKM matrix element $|V_{tb}|$ is expected to be close to unity as a consequence of unitarity and a deviation from this prediction could arise from a fourth quark generation, or simply due to different decay modes. Results obtained in the $t\bar{t}$ dilepton channel are in good agreement with the SM prediction, $R = 0.98 \pm 0.04$ (stat.+syst.), with a lower limit $R > 0.85$ at 95% confidence level (CL) [8].

In $t\bar{t}$ production, top quarks are unpolarized but their spins are correlated. Due to the short lifetime of the top quark, which is smaller than the hadronization scale, the information of the spin correlation is preserved in the decay products. It is possible to measure the spin correlation of the top quark pair from the angular correlation of the decay products. Many models of NP predict different angular distributions from the SM predictions. Spin correlations are measured using dilepton events, where the correlation coefficient is defined as the fractional difference in the number of events with the spins of the top quarks correlated and those with the spin anti-correlated. The LHC results are in good agreement with the SM predictions and exclude the hypothesis of zero spin correlation [9].

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The measurement of the polarization of the W boson from top quark decays is interesting as NP may lead to an anomalous Wtb coupling. Since the spin information is preserved in top quark decay products and the bottom quark mass is small compared to the top and W masses, the SM predicts the W boson to be mostly longitudinally polarized (F_0=69%) or left-handed (F_L=31%) through the V-A coupling. These fractions may significantly change in the presence of anomalous couplings, and may be inferred experimentally from the angular distribution between the lepton from the W decay and the b-jet from the same top quark decay. Measurements show good agreement with the SM predictions, and the results are used to set limits on anomalous Wtb couplings.

In $t\bar{t}$ events, the difference in rapidity (or other) distributions of top and anti-top quarks is usually known as charge asymmetry, which is sensitive to NP models. For example, it probes perturbative QCD predictions and provides tests of NP models where top quark pairs are produced through the exchange of new heavy particles, such as axigluons with anomalous axial-vector coupling of gluons to quarks, Z' bosons, or Kaluza-Klein (KK) excitations of gluons. Recent Tevatron results yield values larger (a 3σ discrepancy) than the SM predictions. At the LHC, in pp collisions, there is no forward-backward asymmetry as the initial state is symmetric. The quantity of interest is the "charge" asymmetry and it shows as a preferential production of top quarks in the forward direction due to the fact that the anti-quarks (from the proton's sea) carry a lower momentum fraction. Differential measurements have been obtained as a function of p_T, y, and invariant mass $m_{t\bar{t}}$ of the top quark pair, and are compatible with SM predictions.

Top quarks are present in many models of NP beyond the SM. Some examples include new particles decaying into top quark pairs, FCNC, anomalous missing transverse energy, same-sign top quark pair production, charged Higgs production. Many extensions to the SM predict interactions with enhanced coupling to the top quarks, resulting as resonances in the $t\bar{t}$ pairs. New particles could be spin-0 scalars or pseudo-scalars, or spin-1 vector or axial-vector particles, such as a Z' boson, a KK gluon or axigluon, or also spin-2 particles. Specific analysis tools have been developed for the searches in the high-mass regions where the top quarks are highly boosted and the decay products tend to be collimated. Searches both in the low- (up to 1 TeV) and in the high-mass (up to several TeV) regions, result in exclusion limits for new particle production rate. Searches for rare decays of top quarks are possible thanks to the large number of top quark events collected. Top quarks decay to a W boson and a bottom quark with a branching fraction of about 100%. However, some extensions of the SM predict that the top quark may also decay to a Z boson and a quark, $t \to Zq$, where q is a u or a c quark. The latter is a decay predicted with a small branching fraction of the order of 10^{-14}, which is beyond the current experimental reach. Therefore, detection of a signal could indicate deviations from the SM predictions. Search for FCNC processes is sought in the tri-lepton final state, where one top $t \to Zq \to llq$ is produced. FCNC can also be sought in the single top production; however, this is experimentally very challenging. Measurements indicate that branching fractions $BR(t \to Zq)$ >0.24% are excluded at 95%CL [10]. New models put forth to explain the larger-than-expected forward-backward asymmetry measurement at the Tevatron require FCNC in the top sector mediated by the t-channel exchange of a new massive Z' boson. These mechanisms would generate same-sign top quark pair production. However, the LHC results disfavor the region of parameter space consistent with the Tevatron forward-backward asymmetry measurement. With even larger data samples, additional studies may shed light on important open questions. Associated production of a Higgs boson with the top quark pair $t\bar{t}$H is important as it would provide direct determination of the top-Higgs couplings, separately for the different Higgs decay modes. Supersymmetry (SUSY) could also affect top quark production. Due to the large top quark mass, the lightest scalar top quark $\tilde{t}_1$ can be the lightest scalar quark and even lighter than the top quark itself. The presence of light top and bottom squarks, charginos and neutralinos could alter the predicted rates through direct stop pair production, through the processes $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ or $\tilde{t}_1 \to t\tilde{\chi}_1^0$. For instance, for a scalar top quark lighter than the top quark, the decay channel $\tilde{t}_1 \to \tilde{\chi}_1^+ (\to \tilde{\chi}_1^0 W) b$ has a similar signature as $t\bar{t}$ events apart from the presence of the neutralinos, whose experimental signature mimics that of a neutrino. More on this topic is discussed in Section 4.

2. Observation of a new boson with a mass of 125 GeV

The discovery of the Higgs boson represents one of the important scientific goals of the LHC experiments, and a cornerstone of particle physics. The SM provides an accurate description of Nature, based on results from earlier experiments. It includes quarks and leptons as the building blocks of matter, and describes their interactions through the exchange of force carriers, but it lacks an intrinsic explanation for the origin of particle masses. The Higgs boson was postulated nearly five decades ago within the framework of the SM and has been the subject of numerous searches at accelerators around the world. Its discovery would verify the existence of a scalar field thought to give mass to three of the carriers of the electroweak force – the W^+, W^- and Z^0 bosons – as well as to the fundamental quarks and leptons. Although the theory does not predict a specific mass for the Higgs boson, the properties of the Higgs boson depend strongly on its mass. General arguments indicate that its mass should be less than about 1 TeV [11].

At the LHC, the SM Higgs boson should be produced through gluon-gluon fusion, through vector boson fusion (VBF) where interacting quarks inside the protons give rise to high energy jets produced at small angles with respect to the beam direction, and associated production (VH), where a vector boson V (either W or Z) is produced together with the Higgs boson. Both VBF and VH events have better signal-to-background ratios relative to gluon fusion, but are far rarer.

A new particle produced in proton-proton collisions at the LHC was recently observed. First hints of a mild excess of events over the expected background were presented in December 2011 (5.0 fb^{-1} at $\sqrt{s}$=7 TeV). With additional data (5.3 fb^{-1} at $\sqrt{s}$=8 TeV) a firm observation was reported in July 2012, yielding a significance of approximately 5 standard deviations over the background-only hypothesis [12]. The search is performed in five decay modes: three modes result in pairs of bosons ($\gamma\gamma$, ZZ, W^+W^-) and two modes yield pairs of fermions ($\tau^+\tau^-$ and $b\bar{b}$). Results are obtained using data samples corresponding to integrated luminosities of 5 fb^{-1} at $\sqrt{s} = 7$ TeV, and 12 fb^{-1} at $\sqrt{s} = 8$ TeV (except for the $\gamma\gamma$ final state that uses 5.3 fb^{-1} of $\sqrt{s} = 8$ TeV data). An excess of events is observed above the expected background, with a local significance of 6.9 standard deviations at a mass near 125 GeV, indicating the production of a new particle. The expected significance for a SM Higgs boson of that mass is 7.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.8 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV [13]. The decay to two photons indicates that the new particle is a boson with a spin different from one. For the ZZ final state, further separation between the signal and background is provided by a discriminant that incorporates the production and decay kinematics, by using observables defined for each event in the 4-lepton center-of-mass frame. A matrix element likelihood approach is used which combines, for each value of the 4-lepton invariant mass (m_{ZZ}), the two dilepton masses (m_{Z1} and m_{Z2}) and other angular variables.

The measured production rate of the signal can be determined for each decay mode individually, and for the overall combination of all channels, normalized to the predicted Higgs boson production rate. The signal strength is defined to be equal to one for the SM Higgs boson. The measured signal strength is highest in the diphoton channel, namely 1.6 ± 0.4, whereas that in the ZZ channel is $0.8^{+0.4}_{-0.3}$ [14]. The best-fit signal strength for all channels combined, expressed in units of the SM Higgs boson cross section, is 0.88 ± 0.21 at the measured mass. The consistency of the couplings of the observed boson with those predicted for the SM Higgs boson is tested in various ways, and no significant deviations are found. Under the assumption that the observed boson has spin zero, the data disfavour the pseudo-scalar hypothesis 0^- with a CL_s value of 2.4%.

The event yields obtained from analyses relative to different decay modes and production mechanisms are consistent with those expected for the SM Higgs boson. Overall, the new particle has properties consistent with those of the SM Higgs boson, although more data are needed to clearly assess its precise nature.

3. Rare decays: $B_{s(d)} \to \mu^+\mu^-$

Rare decays of neutral bottom mesons to muon pairs, $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$, are highly suppressed in the SM and the branching fractions $BR(B_s^0 \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$ and $BR(B_d^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$ are accurately predicted [15]. Hence, these decay modes act as important probes to search for deviations from the SM expectations. The LHCb collaboration recently observed an excess of $B_s \to \mu^+\mu^-$ candidates with respect to the background expectation, with an estimated branching fraction of $BR(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 1.5) \times 10^{-9}$, compatible with SM predictions and corresponding to a signal significance of 3.5 standard deviations [16]. A CMS search for these rare decays is approaching the sensitivity to measure the SM branching ratios [17].

4. Searches for new physics beyond the standard model

It is commonly agreed that the SM is not the "final" model, and search for NP is therefore mandatory. The most challenging of the scientific goals of the LHC experiments is perhaps to solve some of the fundamental puzzles of Nature, such as why we can only account for 5% of the mass in the Universe, and shed light on dark matter or dark energy searches. NP can be probed by either direct searches for new particle production or by precision measurements which may show deviations from expectations.

SUSY is a well known candidate for a theory beyond the SM because it solves the hierarchy problem, it allows the unification of the gauge couplings, and it may provide a candidate particle for dark matter. A comprehensive program of searches for the production of supersymmetric particles has been underway since 2010 at the LHC. Since SUSY models vary widely, these searches target a broad range of possible final states, including purely hadronic states [18], leptonic states with one lepton [19], two leptons of opposite sign [20], two leptons of the same sign [21], and three or more leptons [22, 23], as well as photonic final states [24]. Although larger datasets are expected to be collected at increased energies only in 2015 and beyond, and searches for SUSY or other NP scenarios can be extended significantly, the first three years of operation have already provided ground for improving our current knowledge.

Multilepton final states

Multilepton final state signatures can be quite striking as the signal-to-background ratio is potentially very large. The few examples of multilepton final states in the SM are characterized by well defined kinematical features and cross section values. These processes are often rare when compared to other NP models. Searches for direct electroweak pair production of charginos and neutralinos in supersymmetric models as well as in other models of NP have been performed. Searches sensitive to such processes, with decays to final states that contain two or more leptons, final states with three leptons, with a same-sign lepton pair, and with an opposite-sign lepton pair in conjunction with jets, have been examined. This multilepton signature characterizes SUSY models with pair-production of electroweak charginos $\tilde{\chi}^{\pm}$ and neutralinos $\tilde{\chi}^{0}$, mixtures of the SUSY partners of the gauge bosons and Higgs bosons. Depending on the mass spectrum, the charginos and neutralinos can have significant decay branching fractions to leptons or vector bosons, resulting in final states that contain either on-shell vector bosons or three-lepton states with continuous pair mass distributions. In either case, neutrino(s) and two stable lightest SUSY particle (LSP) dark-matter candidates are produced, which escape without detection and lead to large missing transverse energy in the event. No excesses above the SM expectations are observed. The results are used to exclude a range of chargino and neutralino masses from approximately 200 to 500 GeV in the context of models that assume large branching fractions of charginos and neutralinos to leptons and vector bosons [23].

Same-sign dilepton events

Searches for NP based on isolated same-sign (SS) dileptons, missing transverse energy, and hadronic jets have been performed. In SUSY, SS dileptons can arise, for example, from pair production of colored super-partners (gluinos and/or squarks), with a lepton in the decay chain of each primary SUSY particle; more generally, this signature is sensitive to final states with same-sign W bosons and/or top quarks. The rarity of SS dileptons in the SM makes a search in this final state particularly attractive. All types of charged leptons (e, μ, and hadronically decaying τs) are included in the search, with lepton transverse momentum thresholds as low as 5 GeV for muons, 10 GeV for electrons, and 15 GeV for τs. Additional selection cuts are required to separate background- and signal-dominated regions. These final states are indicators of the possible presence of SUSY particles as well as other possible NP scenarios. There is no evidence of an excess over the expected SM predictions, and a good agreement is found between observed yields and the predicted background. The measurement is used together with the uncertainty on the signal acceptance to set an upper limit on the contribution from NP events, and to constrain SUSY models [21].

Search for the scalar top quark

The SM has been incredibly successful at describing the majority of particle physics phenomena. However, it suffers from such shortcomings as the hierarchy problem, where fine-tuned cancellations of large quantum corrections are required in order for the Higgs boson to have a mass

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of order 100 GeV, at the electroweak symmetry breaking scale. SUSY is a popular extension to the SM which postulates that for each SM particle there exists a superpartner with exactly the same quantum numbers, differing by one half unit of spin. SUSY provides a natural solution to the hierarchy problem through the exact cancellations of the quadratic divergences of the top quark and scalar top squark loops. A search for the pair production of top squarks $\tilde{t}$ is motivated by the fact that relatively light top squarks are necessary if SUSY is to be the "natural", i.e., not fine-tuned, solution to the gauge hierarchy problem. These constraints are especially relevant given the recent discovery of a particle that closely resembles the Higgs boson, with a mass of 125 GeV. The search focuses on two decay modes of the top squark: $\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$ and $\tilde{t} \to b\tilde{\chi}_1^+ \to bW\tilde{\chi}_1^0$, which are expected to have large branching fractions, if kinematically accessible. Here, the neutralinos ($\tilde{\chi}^0$) and charginos ($\tilde{\chi}^+$) are the mass eigenstates formed by the linear combination of the gauginos and higgsinos, fermionic superpartners of the gauge and Higgs bosons. The charginos are unstable and can subsequently decay into neutralinos and W bosons, leading to the processes: $pp \to \tilde{t}\bar{\tilde{t}}^{\star} \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $pp \to \tilde{t}\bar{\tilde{t}}^{\star} \to b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^+ \to b\bar{b}W^+W^-\tilde{\chi}^0\tilde{\chi}^0$. The lightest neutralino $\tilde{\chi}_1^0$ is often considered to be the stable LSP, which escapes without detection and results in large missing transverse energy. The signature of the signal process includes high transverse momentum jets, including two b-jets, and E_T^{miss}. Requiring exactly one isolated high p_T electron or muon suppresses many of the dominant backgrounds present in the all-hadronic channel. The largest backgrounds in the single lepton topology are semi-leptonic decays of $t\bar{t}$ and W+jets events. A summary of the background expectations after applying all the corrections show that the observed yields in the signal regions are in good agreement with the predicted background, and no evidence for an excess is observed. The observed E_T^{miss} distributions for the events in the data are also in agreement with the expected background [25].

Z' and dilepton mass resonances

A number of NP models predict the existence of heavy narrow resonances that decay to lepton pairs. Results of searches for a narrow $Z' \to \ell^+\ell^-$ (ℓ=e, μ) resonance have been performed. A shape-based analysis of the dilepton mass spectra is performed by searching for a peak on a falling smooth distribution with the overall background normalization determined by an unbinned maximum likelihood fit. The data are consistent with the SM expectation, and limits are set on the production cross section times branching fractions of new heavy narrow resonances in dimuon and dielectron invariant mass spectra relative to Z boson production at the 95% CL. Many experimental and theoretical uncertainties cancel in this ratio. The findings exclude, at 95% CL, a Z' with SM-like couplings below 2590 GeV, and the superstring-inspired Z'_ψ below 2260 GeV [26].

Boosted objects

Among the different scenarios for physics beyond the SM are possibilities of new gauge interactions with large couplings to third-generation quarks. These interactions predict new massive states, generically referred to as Z' bosons, that can decay into $t\bar{t}$ pairs. Typical examples are the topcolor Z', and the Randall-Sundrum KK gluons. Other models have recently been proposed to resolve the discrepancy in the forward-backward asymmetry in $t\bar{t}$ production reported at the Tevatron [27]. Model-independent studies of the implications of a large forward-backward asymmetry suggest that a strong enhancement of the production cross section for $t\bar{t}$ pairs would be expected at the LHC for invariant masses $m_{t\bar{t}}$>1 TeV. Several models of resonant $t\bar{t}$ production are considered, including a Z' resonance with a narrow width of 1% of the mass, a Z' resonance with a moderate width of 10% of the mass, as well as broader KK gluon states. The study examines decays of produced $t\bar{t}$ pairs in the all-hadronic channel, taking advantage of the large (44%) branching fraction of $t\bar{t} \to W^+bW^-b \to 6$ quarks. The decay products of these highly boosted top quarks are collimated, and are partially or fully merged into single jets with several separate sub-jets corresponding to the final-state quarks (one from the b quark and two light-flavor quarks from the W decay, from $W \to q\bar{q}'$). No excess of events is observed over the expected yield from SM background sources [28]. Upper limits in the range of 1 pb are set on the product of the Z' cross section and branching fraction for a topcolor Z' modeled for several widths, as well as for a Randall-Sundrum KK gluon.

5. Summary and prospects

The CMS experiment has collected 5 inverse femtobarns of $\sqrt{s} = 7$ TeV proton-proton collisions in the 2011 run of the LHC, and close to 20 inverse femtobarns at $\sqrt{s} = 8$ TeV in 2012. Results obtained with those data range from precision measurements of standard model observables to searches for new physics. Among the most exciting of these results is certainly the observation of a new particle at a mass of 125 GeV, which is possibly the long sought Higgs boson. This observation is independently confirmed by the ATLAS collaboration [29]. One of the most striking conclusions to be drawn from these early results is the lack of hints for any new physics model, as the low-scale supersymmetric models are close to "extinction", although still possible and favored by some. Other exotic new physics models are yet to be seen in the data.

As a long shutdown in the operation of the LHC is foreseen for the next two years, the LHC experiments are preparing for the higher energy run to start in 2015 at (or close to) the design energy of $\sqrt{s}$ =14 TeV. However, the biggest challenge for the LHC team is to be able to provide - highly desirable for the experiments - safe proton-proton collisions with inter-spacing bunches of 25 nanoseconds (as from design), instead of the current operation at 50 nanoseconds. The larger number of bunches in the LHC will allow delivering the same integrated luminosity with reasonable bunch intensities and number of pileup interactions. Detectors were designed and constructed for operating with an average number of 20 pileup events. This number has already been surpassed in the 2012 run, when up to 66 pileup events have been reached for an instantaneous luminosity $\mathscr{L} = 7.7 \times 10^{33}$ cm^{-2}sec^{-1}. During the two year shutdown period, beside the regular detector maintenance activity, the CMS collaboration plans a few upgrade projects aimed at improving the performance of the muon coverage, of the vertex reconstruction with an upgraded pixel detector, and furthermore upgrading the hadron calorimeter.

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